ORIGINAL ARTICLE

Shoulder joint loading in the high performance flat and kick tennis serves

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Objective: To quantify and compare the full body kinematics and shoulder joint kinetics during the high-performance tennis flat (FS) and kick serves (KS).
Methods: A 12-camera 250 Hz, Vicon motion analysis system recorded the three-dimensional FS and KS of 12 high-performance male players. A total of 22 paired Student's t tests, with an accompanying partial Bonferroni correction ($p<0.01$), determined statistically significant differences between the variables of interest in both serves.
Results: Higher peak horizontal, vertical and absolute racquet velocities were developed during the FS, while higher lateral velocities characterised the KS. Similar shoulder joint kinematics and kinetics punctuated both serves, but with some variation in trunk and lower limb mechanics.
Conclusions: Similar shoulder joint kinetics assisted the development of varying three-dimensional racquet velocities in the FS and KS. The comparable shoulder joint loading conditions point to the repetitive, long-term performance of either serve as relevant in shoulder joint injury pathologies.

The shoulder joint is integrally involved in the service action, with rotational velocities of approximately $3000°.s^{-1}$ developed through large ranges of motion (~270° circumduction), believed to contribute ~20% of the total force generated during the stroke.[1] Unsurprisingly, injury to the tennis player's shoulder is often allied to the serve.[2] Superficially, positive associations between serve velocity and shoulder joint loading could implicate the flat power serves (FSs), with their higher horizontal racquet velocities, in shoulder injury.[2] However, Chow *et al*[3] revealed no difference between first and second serve pre-impact racquet speeds, but significant variation in the vector components of racquet velocity. Where higher vertical and lateral racquet velocities were observed to characterise the second serve, the opposite was true for horizontal racquet velocity. Players might therefore experience comparable gross shoulder joint loading in the FS and the serve commonly employed as professional players' second deliveries, the kick serve (KS), but with differential three-dimensional (3D) joint kinetics. The aim of this study was therefore to describe and compare the full body kinematics and shoulder joint kinetics related to loading of the shoulder joint during the high-performance FS and KS.

METHODS

Preparation and performance of subjects

A total of 12 right-handed high-performance male players (mean (SD) height 183.2 (6.8) cm, weight 79.9 (5.6) kg) consented to participate in the study, following approval by the relevant Ethics in Human Research Committee. Subsequent to an appropriate warm-up, the players hit three successful maximal effort FSs and KSs to a 1×1 metre target area bordering the "T" of the first service box. Reliable kinematics and kinetics were derived from normative data of three serves.[4] Successful FSs and KSs were hit with minimal spin and maximum spin ("kick") respectively, before landing in the target area.

Data capture, treatment and statistical analysis

Players were fitted with a customised full-body marker set (62 retro-reflective markers, 16 mm in diameter), in agreement with the "calibrated anatomical systems technique" (CAST)[5] to minimise error related to skin movement artefact and incorrectly located critical anatomical landmarks. A 12-camera 250 Hz, Vicon motion analysis system (Oxford Metrics Inc., Oxford, UK) recorded the 3D marker trajectories, with 3D coordinates expressed in a right-handed inertial reference frame, where the origin was at the centre of the baseline. Positive x was pointing forward, positive y was vertical and pointing upwards, while z was perpendicular to x and y and positive to the right. Segmental masses and moments of inertia were provided via previously published data,[6 7] and a Wilson 6.0 Pro Staff racquet (Amersports, Helsinki, Finland), whose inertial parameters (x: 172.7 $kg.cm^2$, y: 15.3 $kg.cm^2$, z: 188.0 $kg.cm^2$) were calculated as in Brody *et al*,[8] was used by all players.

To permit simultaneous consideration of both pre- and post-impact mechanics, as well as best represent the actual serve movement, data treatment involved deletion and interpolation by Vicon's cubic spline "fill gaps" function of data from one frame pre-impact and five frames post-impact.[4] All raw data were filtered at an established most appropriate mean squared error of 25. Data were then modelled with a customised full body model, which used a Y–X–Y decomposition to describe shoulder joint motion,[4 9–11] while applying the Euler Z–X–Y sequence to describe all other joint movements: flexion(+)/extension(−), adduction(+)/abduction(−) and internal(+)/external(−) rotation of the moving segment coordinate system with respect to the fixed segment coordinate system. Consistent with contemporary reports, shoulder joint force is represented in its component parts: anterior–posterior, superior–inferior, and compressive–distractive. Some caution is required in interpreting compressive, or pulling joint forces, as they can be, depending on muscle activity, compressive or tensile in nature.[12]

Phases, represented by meaningful temporal or kinematic characteristics of the serve, were normalised by customised Matlab software (The Mathworks, Natick, Massachusetts, USA): rear leg drive (from maximum back knee joint flexion

Abbreviations: FS, flat serve; KS, kick serve; TCS, technical coordinate system

Table 1 Comparison of linear racquet kinematics across FS and KS

Linear racquet kinematics	Phase/event	FS†	KS†	t Test	p Value
Maximum absolute velocity ($m.s^{-1}$)	Forwardswing	43.2 (3.1)	40.3 (2.9)	4.410	0.001*
Maximum horizontal velocity ($m.s^{-1}$)	Forwardswing	40.6 (3.4)	35.0 (2.9)	8.502	0.000*
Maximum vertical velocity ($m.s^{-1}$)	Forwardswing	30.0 (3.2)	27.9 (2.9)	3.949	0.002*
Right lateral velocity ($m.s^{-1}$)	IMP	1.4 (5.5)	10.2 (2.3)	6.326	0.000*

*$p<0.01$.
†Mean (SD).

to maximum external rotation of the racquet arm, MER), lead leg drive (from maximum front knee joint flexion, MKF, to MER or as both feet left the ground simultaneously), swing (from MKF to 0.004 s prior to racquet-ball impact, IMP), cocking (from MKF to MER), forwardswing (from MER to IMP) and follow-through (from 0.004 s post racquet-ball impact to subsequent front foot contact with the ground). A total of 22 paired Student's t tests, with an accompanying partial Bonferroni correction ($p<0.01$), delineated statistically significant differences between the kinematic and kinetic variables of interest in both serves.

RESULTS

Effect of serve type on absolute and planar racquet (tip) velocity

Significant differences existed between the pre-impact racquet velocity profiles of the FS and KS (table 1). Where (mean (SD)) higher absolute (43.2 (3.1) $m.s^{-1}$), horizontal (40.6 (3.3) $m.s^{-1}$) and vertical (30.0 (3.2) $m.s^{-1}$) pre-impact racquet velocities characterised the FS, players generated higher right lateral racquet velocities at impact for the KS (10.2 (2.3) $m.s^{-1}$; FS: 1.4± (5.5) $m.s^{-1}$). Figure 1 illustrates these differential mean racquet velocity profiles during the forwardswing of both serves.

Body kinematics that characterise serve performance

Upper arm MER approximated a mean (SD) of 115 (15)° for both serves and was antecedent to the upper arm moving through ~40° of longitudinal rotation at high speeds (mean: 10.4–10.8 $rad.s^{-1}$) during the forwardswing. The upper arm plane of elevation angle at MER and upper arm elevation with respect to the thorax at impact were also independent of serve type.

As compared with the pelvis, the shoulders were similarly laterally flexed to the right at MKF in the FS and KS (table 2). At impact however, the 3D alignment of the shoulders (with respect to the global coordinate system) varied significantly between serves. That is, where the shoulders were more rotated (ie, front-on; FS: 41.6± (18.5)°; KS: 64.4 (14.3)°) and tilted to the left (FS: 41.7 (7.8)°; KS: 33.4 (10.2)°) in the FS, they were flexed further forward in the FS (67.2 (9.4)°; FS: 56.4 (15.1)°).

Maximum front knee joint flexion (~74 (18)°) was consistent for both serves, yet peak velocity of front knee joint extension trended higher in the KS. The difference observed in the peak vertical velocity of the rear hip between serves (FS: 2.1 (0.3) $m.s^{-1}$; KS: 2.3 (0.3) $m.s^{-1}$) also points to some differential higher order lower limb kinematics characterising the FS and KS.

Shoulder joint kinetics that characterise the FS and KS

No significant differences were recorded in the shoulder joint kinetics of the FS and KS (table 3). During the cocking phase of both serves, players developed homogeneous maximum anterior forces (FS: 167.3 (46.7) N; KS: 160.4 (52.5) N) at comparable rates (FS: 208.3 (56.2) $N.s^{-1}$; KS: 189.9 (55.9) $N.s^{-1}$). Peak internal rotation moments approximating 23 Nm were also generated during the forwardswing irrespective of serve type.

Similar pre-impact compressive force profiles punctuated the performance of both serves. More specifically, average rates of maximum compressive force loading were near to 325 $N.s^{-1}$ and mean compressive forces approximated 220 N regardless of serve performed. Further non-significant differences marked the post-impact shoulder joint kinetics of the FS and KS. However, there was some suggestion of mean compressive forces (FS: 87.1 (39.6) N; KS: 75.7 (32.5) N) and peak external

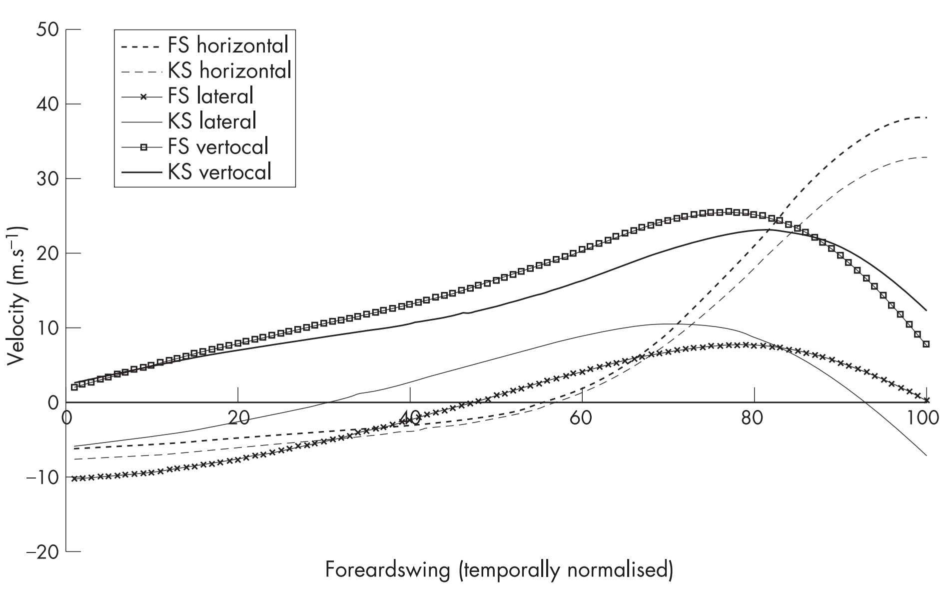

Figure 1 Comparison of mean three-dimensional (3D) linear racquet velocities during the forwardswing of the FS and KS.

rotation moments (FS: 18.8 (10.0) N; KS: 14.7 (6.6) N) trending higher during the follow-through of the FS.

DISCUSSION

Effect of serve type on 3D racquet velocity

The significantly higher pre-impact horizontal and vertical racquet velocities of the FS and higher right lateral velocities of the KS were in agreement with previously reported differential velocity profiles.[3] From a practical standpoint, these differences are related to the divergent ball toss locations across serves. For example, the displacement of the ball toss significantly further forward in the FS[3] likely facilitates the development of high horizontal racquet velocities, whereas the KS, with its exaggerated lateral ball toss position, would theoretically favour the generation of higher right lateral racquet velocities. Tangentially, the higher peak pre-impact vertical racquet velocities developed in the FS (30.0 (3.2) $m.s^{-1}$; KS: 27.9 (2.9) $m.s^{-1}$) might have assisted players in attaining higher hitting positions (relative to standing height (ST); FS: $\sim$1.56×ST; KS: $\sim$1.52×ST) at impact.

Of further interest is that where Chow *et al*[3] reported professional male players to generate similar pre-impact absolute racquet velocities in first and second serves ($\sim$38 $m.s^{-1}$), the players in this study developed significantly higher absolute 3D velocities in the FS (43.2 (3.1) $m.s^{-1}$) than in the KS (40.3 (2.9) $m.s^{-1}$). This variance could be explained by methodological incongruence. In the current investigation, all players were instructed to hit maximal effort FS and KS to location. Contrastingly, although Chow *et al*[3] controlled, in part, for ball placement, the first and second serves were hit during tournament play and likely with varying tactical intent (ie, slice or topspin), thereby confounding the comparison of absolute 3D velocities between specific types of serves.

Variation in body kinematics in the FS and KS

The tilted alignment of the shoulders and pelvis coincides with MKF, and is considered by many coaches as key to high-speed serving. Termed the "power" — or "trophy" — position, it is believed to trigger resultant knee extension and trunk rotation, which in turn is associated with improved serve performance.[13 14]

Maximum front knee flexion was similar for the FS (73 (19)°) and KS (74 (17)°), and consistent with that which is advocated in the coaching literature.[15] While this characteristic is readily observable, it should not form the sole basis upon which coaches evaluate "leg drive" as the peak vertical velocity of the rear hip in the KS (2.3 (0.3) $m.s^{-1}$) was significantly higher than in the FS (2.1 (0.3) $m.s^{-1}$). The peak front knee extension angular velocity trended similarly higher in the KS, albeit magnitudes were modest in comparison to the 14.0 (7.0) $rad.s^{-1}$ reported by Fleisig *et al.*[16] Together, these characteristics appear to suggest that more vigorous lower limb drives punctuate the KS.

If KSs are indeed characterised by more dynamic leg drives, intuitively it could be surmised that the magnitude of upper arm external rotation would also be more pronounced than in the FS.[17] However, MER of the upper arm approximated 115 (15)° and so failed to support this affirmation. At MER, analogous mean upper arm plane of elevation angles characterised the KS and FS. Significantly, only one subject recorded an angle >180° at MER such that the upper arms of all other subjects largely remained in front of their shoulder joint alignments. This mean upper arm plane of elevation position is comparable to the previously reported 7 (9)° of upper arm horizontal adduction at the same reference point of the serve.[16] It would therefore appear that hyperangulation, contributing to secondary impingement, is not a cause of concern among most players executing FSs and KSs.

The above-mentioned mean upper arm MER is sizeably less than the 170–185° of rotation previously reported to characterise the serve and baseball pitch.[16 18–20] Similarly, the recorded mean peak upper arm internal rotational velocities amount to $\sim$25% of the 2000–3000°.s^{-1} detailed in past investigations of serve kinematics.[1 16 21] This anomaly would appear to be related to methodological differences between studies and potential systematic error. For example, earlier research efforts utilised the direct linear transformation method and modelling techniques that were restricted to inter-segment vector comparisons projected onto planes, rather than the elaboration of anatomical coordinate system matrices from the position of technical coordinate systems (TCSs) as performed in this study. The limitations of these approaches in accurately computing humeral rotation have received previous critical comment.[22] The customised marker set attempted to negotiate these limitations and correctly replicate 3D humeral motion via the TCS of the humerus. However, the design and more pertinently alignment of the humeral triad near the soft tissue of the upper arm likely manifested in reduced shoulder joint longitudinal rotation kinematics and hence kinetics when compared with those calculated through inter-segment vector comparisons. Indeed, Gordon and Dapena[22] highlighted similar error to confound the calculation of axial rotation of the upper arm in their recent evaluation of the contribution of joint rotations to serve speed.

The lateral flexion separation angle of $\sim$31° at MKF for the FS and KS is consistent with that expected of the "power"

Table 2 Upper and lower body kinematics that characterise the FS and KS, and that are reported to relate to shoulder joint loading in the serve

Kinematic characteristic	Event/phase	FS‡	KS‡	t Test	p Value
Maximum external rotation of the racquet shoulder (°)	MER	115.9 (18.3)	119.0 (18.3)	0.693	0.502
Upper arm plane of elevation angle (°)†	MER	158.9 (8.5)	161.5 (10.2)	2.407	0.035
Peak shoulder joint internal rotation angular velocity ($rad.s^{-1}$)	Forwardswing	10.8 (4.7)	10.6 (3.1)	−0.594	0.564
Upper arm–thorax elevation angle (°)	IMP	108.9 (14.1)	107.7 (19.7)	0.335	0.744
Left lateral flexion shoulder–pelvis alignment separation angle (°)	MKF	31.5 (7.3)	31.6 (7.5)	−0.121	0.906
Shoulder alignment left lateral flexion (°)	IMP	41.7 (7.8)	33.4 (10.2)	−3.903	0.002*
Shoulder alignment right rotation (°)	IMP	41.6 (18.5)	64.4 (14.3)	7.152	0.000*
Shoulder alignment forward flexion (°)	IMP	56.4 (15.1)	67.2 (9.4)	−3.865	0.003*
Maximum front knee joint flexion (excluded angle, °)	MKF	73.4 (19.3)	74.6 (17.1)	−1.324	0.212
Peak front knee joint extension angular velocity ($rad.s^{-1}$)	Lead leg drive	7.6 (2.0)	8.2 (1.8)	2.795	0.017
Maximum rear hip vertical velocity ($m.s^{-1}$)	Rear leg drive	2.1 (0.3)	2.3 (0.3)	−3.927	0.002*

*$p<0.01$.
†180° represents upper arm horizontal adduction, parallel to the trunk; <180° sees upper arm position in front of this straight line (fig 2).
‡Mean (SD).

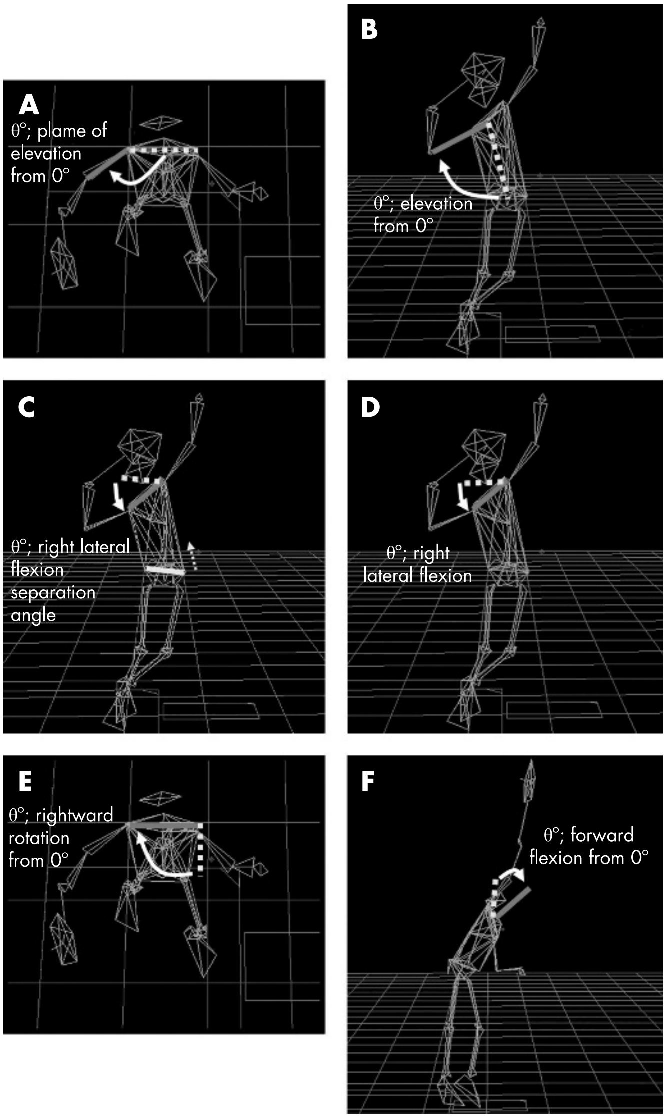

Figure 2 Two-dimensional planar representation of three-dimensional angular measures: (A) plane of elevation, (B) upper arm–thorax elevation, (C) lateral flexion shoulder–pelvis alignment separation angle, (D) shoulder alignment lateral flexion, (E) shoulder alignment rotation and (F) shoulder alignment forward flexion.

position described above. Noteworthy is that the need to maintain balance and the large range of motion of the trunk dictates that the magnitude of lateral pelvis flexion will be less than that which is possible at the shoulders. Nonetheless, the greater lateral flexion of shoulder alignment—and by extension, the trunk—to a player's racquet side would, when complemented by back leg drive, assist players to produce more angular momentum about the anterior–posterior axis of the trunk and better transfer angular momentum to the upper limb.[13 17] To this end, Bahamonde[13] illustrated those players whom produced greater angular momentum through lateral trunk flexion (toward from the non-hitting shoulder) during the forwardswing to impact served with higher ball speeds. Given the comparable laterally flexed alignments that describe the FS and KS at MKF of this sample, it appears likely that high-performance players align their trunks to generate angular momentum about the anterior–posterior axis of the trunk independent of serve type. While certainly plausible, the 3D alignment of the shoulders at impact varied significantly between FS and KS, suggesting that the fashion in which the trunk rotates during the forwardswing does differ between serves. That is, at impact the alignment of the shoulders was significantly more rotated (toward impact), tilted to the left and extended (upright) in the FS than in the KS. Indications are thus that the forwardswing of the FS might be characterised by larger amounts of lateral trunk flexion and trunk rotation, while more forward flexion is involved in the execution of the KS. The fact that Chow *et al*[3] found increased abdominal muscle activity in the upward swing of the topspin serve as compared with that of flat or slice serve could support this latter assertion.

In spite of this differential 3D shoulder alignment at impact, the angle of upper arm elevation with respect to the thorax approximated 110° for both serves. This finding is consistent with the 101 (11)° of shoulder abduction that Fleisig *et al*[16] reported to characterise the upper extremity motion of professional players at serve impact. Significantly, it is also similar to the angle of 100 (10)° that Matsuo *et al*[20] detailed as producing maximum pitching ball velocity and minimum shoulder loading in baseball pitching.

Relationship between serve type and shoulder joint kinetics: implications for injury and performance

None of the seven variables considered to represent shoulder joint load differed across serve type. Furthermore, as selected racquet and body kinematics were shown to vary with serve type, it is likely that kinetic analyses of other joints would unearth technique-related differences. Equally, it would appear logical that individual players subjected to higher loading conditions in a FS or KS might be more likely to sustain shoulder joint injury with repeated performance of that serve.

Cocking

Peak anterior forces of ~165 N were recorded during the cocking phase of both the FS and KS. Similarly, the average rate of peak anterior force loading was homogeneous between serves, with mean (SD) rates of 208.3 (56.2) $N.s^{-1}$ and 189.9 (55.9) $N.s^{-1}$ punctuating the FS and KS respectively. These comparable anterior force loading profiles might therefore suggest that the anterior capsule and ligaments of the

Table 3 Comparison of shoulder joint kinetics considered to represent shoulder joint load across FS and KS (n = 12)

Shoulder joint forces and moments	Event/phase	FS*	KS*	t Test	p Value
Maximum anterior force (N)	Cocking	167.3 (46.7)	160.4 (52.5)	−0.555	0.590
Average rate of maximum anterior force loading ($N.s^{-1}$)	Cocking	208.3 (56.2)	189.9 (55.9)	−1.435	0.179
Peak internal rotation moment (Nm)	Forwardswing	22.7 (7.6)	23.5 (5.4)	0.423	0.680
Average rate of maximum compressive force loading ($N.s^{-1}$)	Swing	333.8 (61.3)	321.2 (83.8)	1.021	0.329
Mean compressive force (N)	Forwardswing	228.6 (52.4)	210.7 (54.2)	1.571	0.144
Mean compressive force (N)	Follow-through	87.1 (39.6)	75.7 (32.5)	2.644	0.023
Peak external rotation moment (Nm)	Follow-through	18.8 (10.0)	14.7 (6.6)	1.840	0.093

*Mean (SD).

What is already known on this topic

- Injury to the tennis player's shoulder is not uncommon, and is often allied to the serve.
- Previous reports have revealed a positive relationship between serve velocity and shoulder joint loading.

What this study adds?

- Different racquet velocity profiles are developed during the execution of the high-performance, male flat and kick serves.
- The shoulder joint kinetics, and by extension shoulder joint loads, that support these disparate profiles are generated independent of the type of serve performed.

glenohumeral joint are similarly stressed near MER independent of serve type. These passive structures play an important role in limiting anterior translation of the humeral head to mitigate the prospect of glenohumeral instability.

Previous kinetic analyses of the tennis serve have not reported peak anterior forces prior to or at MER; preferring to report maximum values during the forwardswing. Consequently, the larger peak anterior forces reported by Noffal and Elliott (445 N;[23]) and Elliott *et al* (males: 291.7 (119.8) N; females: 185.1 (60.9) N,[2]) could be typical of the forwardswing to impact.

Forwardswing

As intimated above, internal rotation of the upper arm is considered key to the development of high racquet velocities in the serve. Indeed, Elliott *et al*[21] have demonstrated that this longitudinal rotation of the upper arm contributes upward of 40% of the horizontal velocity of the racquet at impact. Of subsequent and recent investigative interest has been the magnitude of the internal rotation moments that generate this rotation during the forwardswing of the serve. For example, Elliott *et al*[2] observed peak shoulder internal rotation torques of 71.2 (15.1) Nm and 47.8 (16.3) Nm for male and female professional players respectively, while Bahamonde[24] reported lower torques (33 Nm) to drive upper arm longitudinal rotation just prior to impact. Comparatively smaller peak internal rotation moments were generated during the FS (22.7 (7.6) Nm) and KS (23.5 (5.4) Nm) forwardswings of players in this sample. As aforementioned, these lower values likely relate to divergent data collection and modelling techniques. However, with high horizontal racquet velocities more central to the foremost tactical goal of the FS as compared with the KS, higher peak internal rotation moments were expected to punctuate the forwardswing of the FS. This contention was not supported (0.423, $p = 0.680$) and players would appear to develop similar peak pre-impact internal rotation moments independent of serve type.

Throughout the extension and internal rotation of the upper arm to impact, portions of the rotator cuff (along with associated connective tissue, the joint capsule and biceps) need to provide the compressive force necessary to centre the humeral head in the glenoid fossa (Blevins, 1997). Ultimately, failure to do so would result in superior migration of the humeral head and the supraspinatus or biceps muscles impinging under the coraco-acromial arch (secondary impingement,[25 26]). Throughout the forwardswing to impact, the mean compressive force applied to the upper arm approximated ~220 N in the FS and KS; with no discrimination between serve types. Similarly, poor distinction was made between the FS and the KS according to their average rates of compressive force loading. So, as players seem to generate pre-impact compressive forces of similar magnitudes and at similar rates during the performance of the FS and KS, secondary impingement brought on by high compressive force loading conditions seems no more likely in the FS than it is during the KS.

Follow-through

In spite of some evidence implicating the FS in marginally higher post-impact shoulder joint loading conditions, the results of the paired comparisons suggest that no distinctive loading profile characterises the follow-through of either serve. Deceleration of the continued internal rotation of the upper arm is facilitated by similar peak FS (18.8 (10.0) Nm) and KS (14.7 (6.6) Nm) post-impact external rotation moments. By extension it might be suggested that the rotator cuff musculature that is reported to eccentrically contract to resist distraction, horizontal adduction and internal rotation of the humerus during the follow-through phase of high-speed overhand sports skills such as the tennis serve,[27 28] is at no greater risk of tensile failure, muscle strain or tear through repeated deceleration of FS or KS racquet and upper-extremity motion.

As in the forwardswing, indications are also that selected shoulder muscles need to produce ~80 N of mean post-impact compressive force to resist humeral distraction in the FS and KS. As theorists have typically preferred to postulate rather than quantify post-impact shoulder joint kinetics, comparisons of the reported magnitudes of post-impact force and torque to the literature are not possible.

CONCLUSION

Players generate significantly higher pre-impact horizontal, vertical and absolute racquet velocities in the FS as compared with the KS. Conversely, higher lateral velocities are developed during the forwardswing of the KS. The shoulder joint kinetics that contribute to these differential velocity profiles do not however vary depending on the type of serve performed. Nonetheless, it should be noted that individual players whom experience higher loading conditions in a FS or KS might indeed be more susceptible to shoulder joint pathologies through repetitive, long-term performance of that serve.

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REFERENCES

1 **Kibler WB**. Biomechanical analysis of the shoulder during tennis activities. *Clin Sports Med* 1995;**14**:79–85.
2 **Elliott B**, Fleisig G, Nicholls R, *et al*. Technique effects on upper limb loading in the tennis serve. *J Sci Med Sport* 2003;**6**:76–87.
3 **Chow JW**, Carlton LG, Lim YT, *et al*. Comparing the pre- and post-impact ball and racquet kinematics of elite tennis players' first and second serves: a preliminary study. *J Sports Sci* 2003;**21**:529–37.
4 **Reid M**. *Loading and velocity generation in the high performance tennis serve*, PhD dissertation.University of Western Australia, 2007.
5 **Cappozzo A**. Compressive loads in the lumbar vertebral column during normal level walking. *J Orthop Res* 1984;**1**:292–301.

6 **Clauser CE**, McConville JT, Young JW. Weight, volume and centre of mass segments of the human body. *AMRL technical report 69–70*. Dayton, Ohio, USA: Wright-Patterson Air Force Base, 1969.
7 **de Leva P**. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech* 1996;**29**:1223–30.
8 **Brody H**, Cross R, Lindsey C. *The physics and technology of tennis*. Solana Beach, California, USA: Racquet Tech Publishing, 2002.
9 **Cheng PL**. A spherical rotation coordinate system for the description of three-dimensional joint rotations. *Ann Biomed Eng* 2000;**28**:1381–92.
10 **Doorenbosch CA**, Harlaar J, Veeger DH. The globe system: An unambiguous description of shoulder positions in daily life movements. *J Rehabil Res Dev* 2003;**40**:147–55.
11 **Wu G**, van der Helm FC, Veeger HE, *et al*. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: Shoulder, elbow, wrist and hand. *J Biomech* 2005;**38**:981–92.
12 **Cholewicki J**, McGill SM. EMG assisted optimization: a hybrid approach for estimating muscle forces in an indeterminate biomechanical model. *J Biomech* 1994;**27**:1287–9.
13 **Bahamonde RE**. Changes in angular momentum during the tennis serve. *J Sports Sci* 2000;**18**:579–92.
14 **Elliott B**. The serve. *ITF Coaching and Sport Science Review*, **24**:3–5.
15 **Elliott B**, Alderson J. Biomechanical performance models. In: Elliott B, Reid M, Crespo M, eds. *ITF biomechanics of advanced tennis*. London, UK: ITF Ltd, 2003:155–75.
16 **Fleisig G**, Nicholls R, Elliott B, *et al*. Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomech* 2003;**2**:51–64.
17 **Elliott BC**. The serve: a biomedical perspective. *Sports Med* 1988;**6**:285–94.
18 **Dillman CJ**, Fleisig GS, Andrews JR. Biomechanics of pitching with emphasis upon shoulder kinematics. *J Orthop Sports Phys Ther* 1993;**18**:402–8.
19 **Escamilla RF**, Fleisig GS, Zheng N, *et al*. Kinematic comparisons of 1996 olympic baseball pitchers. *J Sports Sci* 2001;**19**:665–76.
20 **Matsuo T**, Matsumoto T, Mochizuki Y, *et al*. Optimal shoulder abduction angles during baseball pitching from maximal wrist velocity and minimal kinetics viewpoints. *J Appl Biomech* 2002;**18**:306–20.
21 **Elliott B**, Marshall R, Noffal G. Contribution of upper limb segment rotations during the power serve in tennis. *J Appl Biomech* 1995;**11**:433–42.
22 **Gordon BJ**, Dapena J. Contributions of joint rotations to racquet speed in the tennis serve. *J Sport Sci* 2006;**24**:31–49.
23 **Noffal G**, Elliott B. *Three-dimensional kinetics of the shoulder and elbow joints in the high performance tennis serve: Implications for injury*. Paper presented at the 4th International Conference of Sports Medicine and Science in Tennis, Coral Gables, Florida, 1998. Florida, USA: USTA Press.
24 **Bahamonde RE**. *Kinetic analysis of the serving arm during the performance of the tennis serve*. Paper presented at the XIIth International Society of Biomechanics, Los Angeles, 1989. Los Angeles, USA: UCLA Press.
25 **Fleisig GS**, Andrews JR, Dillman CJ, *et al*. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med* 1995;**23**:233–9.
26 **Blevins FT**. Rotator cuff pathology in athletes. *Sports Med* 1997;**24**:205–20.
27 **Fleisig GS**, Barrentine SW, Escamilla RF, *et al*. Biomechanics of overhand throwing with implications for injuries. *Sports Med* 1996;**21**:421–37.
28 **Jobe FW**, Moynes DR, Tibone JW, *et al*. An EMG analysis of the shoulder in pitching: a secondary report. *Am J Sports Med* 1984;**12**:218–20.

COMMENTARY

This paper provides detailed analysis of the kinetics of the shoulder joint during the performance of flat and kick serves. Although the flat serve has been analysed extensively, very few studies have looked at the mechanics of the kick serve. Information on the torque generated at the shoulder is important as it provides a better understanding of muscular activity, which could be use to evaluate the vulnerability to injury.

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